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FATIGUE LIFE VARIABILITY IN ALUMINIUM ALLOY AIRCRAFT STRUCTURES

by

G. S. JOST and S. P. COSTOLLOE

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SUMMARY

A survey of variability in the fatigue lives of aluminium alloy aircraft structures tested under gust and manoeuvre loadings using programmed and random sequences has shown that scatter associated with gust loading is significantly higher than that for manoeuvre loading. By contrast, there appears to be no systematic effect of loading sequence.

The data have been treated both as lognormal and Weibull distributed.

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16. *ABSTRACT*

A survey of variability in the fatigue lives of aluminium alloy aircraft structures tested under gust and manoeuvre loadings using programmed and random sequences has shown that scatter associated with gust loading is significantly higher than that for manoeuvre loading. By contrast, there appears to be no systematic effect of loading sequence.

The data have been treated both as lognormal and Weibull distributed.

CONTENTS

NOTATION

f	function
i	failure number, $1 \leqslant i \leqslant n$
k	sample number, $1 \leqslant k \leqslant m$
n	number in the sample
m	number of sample
s	sample standard deviation of log life
x	fatigue life
y	log x
α	dispersion parameter of Weibull distribution
β	location parameter of Weibull distribution
Γ	gamma function
ν_k	degrees of freedom of k^{th} sample $= n_k - 1$
Σ	sum
σ	standard deviation of log normal distribution
μ	mean of log normal distribution
$\hat{\sigma}$	pooled sample estimate of σ
$\hat{\alpha}$	pooled sample estimate of α.

1. INTRODUCTION

Since an earlier report on this subject was issued in 1971[1], additional data on fatigue life variability in aircraft structures have been published. In Reference 1 data on scatter arising from full scale fatigue tests on many aluminium alloy aircraft structures were analysed on the basis of the log normal distribution. Data pooling permitted the establishment of typical values for given types of loading and/or sequence. It was considered worthwhile repeating the exercise to include the additional data, and to treat the total body of data also in terms of the two parameter Weibull distribution.

2. DATA

The opportunity has been taken to make some improvements to the earlier report. First, neither the constant amplitude data nor the notched specimen data given there are included here. The relevance of such data to service sequence loading and to real structures, respectively, is now recognised as rather remote, and the present adequate and far more appropriately based data make their use unnecessary.

The variable amplitude data of the original report were classified into symmetric and asymmetric loadings, and those which included ground to air cycles. These categories have been retained but the first two have been retitled gust loading and manoeuvre loading respectively. Loadings in the former category are symmetrical about the 1 g level and are typical of civil or transport aircraft, whilst manoeuvre loadings are characterised by a marked asymmetry typical of, for example, fighter aircraft. All of the additional published data fall into the manoeuvre loading category which now contains over 160 individual test results.

Finally, the source data used for subsequent analysis were not included in the earlier report. That omission is rectified here in Tables 1, 2 and 3 where the details of the data from gust loading, manoeuvre loading and from loadings which included ground to air cycles are given.

It is to be noted that the data considered here have all been generated prior to the general introduction of closed loop servo (or load feedback) fatigue testing equipment with its inherent precision and long term stability. The indications from data obtained on specimens and components under more representative testing and/or more modern testing equipment are that the scatter associated with such tests results does, if anything, tend to decrease. The present scatter estimates may therefore be considered as representing upper variability bounds.

3. ANALYSIS

The data have been fitted to the log normal and Weibull distributions. Defining $y = \log x$, where x represents fatigue life in cycles or hours, the normal distribution of y is given by

$$f(y) = (\sigma\sqrt{2\pi})^{-1} \exp\left[-\tfrac{1}{2}\left((y-\mu)/\sigma\right)^2\right]$$

where μ and σ^2 are the mean and variance respectively, their estimators from a sample of size n being given by

$$\bar{y} = \sum_{i=1}^{n} y_i/n$$

$$s^2 = \sum_{i=1}^{n} (y_i - \bar{y})^2/(n-1)$$

For the Weibull distribution

$$f(x) = (\alpha/\beta)(x/\beta)^{\alpha-1} \exp\left[-(x/\beta)^{\alpha}\right]$$

where α and β are the dispersion and location parameters of x respectively, their maximum likelihood estimators being given by

$$\hat{\alpha} = n\sum_{i=1}^{n} x_i^{\hat{\alpha}} \Bigg/ \left[n\sum_{i=1}^{n} x_i^{\hat{\alpha}} \ln x_i - \left(\sum_{i=1}^{n} \ln x_i \right) \Bigg/ \sum_{i=1}^{n} x_i^{\hat{\alpha}} \right]$$

and

$$n\hat{\beta}^{\hat{\alpha}} = \sum_{i=1}^{n} x_i^{\hat{\alpha}}$$

Estimates of μ and σ and of α and β for the data of Tables 1, 2 and 3 are given in Tables 4, 5 and 6. In these latter, program loading data have been separated from random loading data.

The final steps are taken in Table 7 for the lognormal analysis, and in Table 8 for the Weibull analysis where the results of pooling of variabilities of like groups of test data are presented*. The data have been pooled as follows: For the data treated as log normal

$$\hat{\sigma}^2 = \sum_k \nu_k S_k^2 / \sum_k \nu_k ,$$

and as Weibull (see Appendix)

$$\hat{\alpha} = \sum_k n_k \Big/ \sum_k \left[n_k \left(\sum_i x_{ik}^{\hat{\alpha}} \ln x_{ik}\right) \Big/ \left(\sum_i x_{ik}^{\hat{\alpha}}\right) - \sum_i \ln x_{ik} \right].$$

Considering first the lognormal analysis, Table 7, the additional data confirm the values previously established:

(1) for gust loading, $\hat{\sigma} = 0{\cdot}14$

(2) for manoeuvre loading $\hat{\sigma} = 0{\cdot}09$

(3) the ground to air cycle data are too limited to permit generalised conclusions: their inclusion in the earlier categories does not significantly alter the above values, and

(4) loading sequence (program versus random) has no significant effect upon *variability* in fatigue life.

The corresponding Weibull analysis gives, for estimates of typical dispersion parameters:

(1) for gust loading $\hat{\alpha} = 3{\cdot}9$, and

(2) for manoeuvre loading $\hat{\alpha} = 6{\cdot}2$.

Rounding these to the nearest whole numbers, $\hat{\alpha} = 4$ for civil flying and $\hat{\alpha} = 6$ for military fighter flying. The former is in agreement with another estimate for civil aircraft[17].

It is of interest to contrast the $\hat{\alpha}$ and $\hat{\sigma}$ estimates for the various groups of data of Tables 4, 5 and 6. This is shown in Figure 1. On average a straight line relationship between $1/\hat{\alpha}$ and $\hat{\sigma}$ fits the data points well, and is given by

$$\hat{\alpha}\hat{\sigma} = 0{\cdot}6.$$

4. CONCLUSIONS

Analysis of the fatigue lives of over 200 variable amplitude fatigue tests on aluminium alloy aircraft structures indicates that

(1) Variability in fatigue life may be characterised by the following typical values of dispersion parameter:

* In Reference 1, the question of whether scatter in fatigue life varied with life was examined. It was concluded there that the life range of the data was too limited to allow resolution of this point. The additional data included here do not alter this conclusion.

Loading Sequence	Data treated as	
	Log Normal $\hat{\sigma}$	Weibull $\hat{\alpha}$
Gust	0·14	3·9
Manoeuvre	0·09	6·2

(2) These values are statistically independent of whether the loading sequence was program or random.

(3) These results are not significantly altered by the inclusion of the very limited available data from sequences which included the ground to air cycle.

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APPENDIX

Pooling of Weibull Dispersion Estimates

By D. G. Ford

Suppose there are m samples each of size n_k, $k = 1$ to m, from different Weibull populations with location parameter β_k but a common dispersion parameter, α, then

$$f(x_k) = (\alpha/\beta_k)(x_k/\beta_k)^{\alpha-1} \exp[-(x_k/\beta_k)^\alpha]$$

and the likelihood function is

$$\prod_k \left\{ \prod_{i=1}^{n_k} (\alpha/\beta_k)(x_{ik}/\beta_k)^{\alpha-1} \exp[-(x_{ik}/\beta_k)^\alpha] \right\} = e^L \text{ say.}$$

Then

$$L = \sum_k n_k \ln \alpha - \alpha \sum_k n_k \ln \beta_k + (\alpha - 1) \sum_k \sum_i \ln x_{ik} - \sum_k \sum_i (x_{ik}/\beta_k)^\alpha \tag{1}$$

Maximum likelihood estimators of α and β_k are found by putting $\partial L/\partial\alpha = 0$ and $\partial L/\partial\beta_k = 0$. For the location parameter

$$\frac{\partial L}{\partial \beta_k} = -\alpha n_k/\beta_k + \alpha \sum_{i=1}^{n_k} x_{ik}{}^\alpha/\beta_k{}^{\alpha+1} = 0$$

and

$$\hat{\beta}_k{}^{\hat{\alpha}} = \sum_{i=1}^{n_k} x_{ik}{}^{\hat{\alpha}}/n_k\,. \tag{2}$$

For the dispersion parameter

$$\frac{\partial L}{\partial \alpha} = \sum_k n_k/\alpha - \sum_k n_k \ln \beta_k + \sum_k \sum_{i=1}^{n_k} \ln x_{ik} - \sum_k \sum_{i=1}^{n_k} (x_{ik}/\beta_k)^{\hat{\alpha}} \ln (x_{ik}/\beta_k) = 0$$

which, after simplifying and substituting for β_k from (2) becomes

$$\hat{a} = \sum_k n_k \Big/ \sum_k \left[n_k \left(\sum_{i=1}^{n_k} x_{ik}^{\hat{\alpha}} \ln x_{ik} \right) \Big/ \left(\sum_{i=1}^{n_k} x_{ik}{}^{\hat{\alpha}} \right) - \sum_{i=1}^{n_k} \ln x_{ik} \right]. \tag{3}$$

For its solution Equation (3) requires iterative substitution for $\hat{a}$: the process is programmed at A.R.L.

TABLE 1

Fatigue Life Data—Gust Loading

Group No.	Reference	Structure	Cycles	Group No.	Reference	Structure	Cycles
1	8 Table VII	Mustang	2418000	5	7 Table 98	Builtup	880000
		Wing	1000000			Panel	1008000
		(24S-T)	1485000			(7075-T6)	
			1400000	6	7 Table 98	Builtup	904000
						Panel	776000
						(7075-T6)	928000
2	8 Table VII	Mustang	1082000				
		Wing	1016000				
		(24S-T)	820000	7	9 Table 2	Friendship	195182
			801000			Wing	247360
			1951000			(7075-T6)	
			1994000	8	8 Table VIII	Mustang	5344000
			1396000			Wing	2751000
						(24S-T)	1626000
							3707000
3	2 Table 3	Commando	8950350				4060000
		Wing	8652005				2423000
		(24S-T)	10322737				2340000
			7160280				3598000
			13067511				2249000
			10919427				1390000
4	3 Table V	Commando	531063				
		Wing	722007	9	9 Table 2	Friendship	208710
		(24S-T)	584766			Wing	146870
			733941			(7075-T6)	

TABLE 2

Fatigue Life Data—Manoeuvre Loading

Group No.	Reference	Structure	Cycles	Group No.	Reference	Structure	Cycles
1	6 Table 15	Builtup	63300	12	10 Table 4	Piston	108592
		Structure	62272			Provost	88400
		(7075)	85958			Wing	137296
			52805				132912
							141376
2	6 Table 16	Builtup	63128				183376
		Structure	75936				176608
		(7075)	68408				144608
			47288				112208
							150016
3	7 Table 98	Builtup	480000				177552
		Panel	736000				178752
		(7075–T6)	960000				160864
							142464
							167744
4	4 Table VI	Fighter	52170				148144
		Wing	40348				108560
			38549				138560
							162352
5	4 Table VI	Fighter	82332				152752
		Wing	77291				153168
							130768
6	4 Table V	Fighter	22682				155200
		Tail	38629				154000
			33992				158400
							190128
7	4 Table V	Fighter	113209				166624
		Tail	93770				122080
			67309				165824
							158320
8	4 Table V	Fighter	107560				166528
		Tail	74536				189328
			109572				121552
							175104
9	4 Table V	Fighter	45459				118192
		Tail	50883				177408
			35256				131600
							190192
10	4 Table V	Fighter	31680				123088
		Tail	37020				214752
			40160				245552
11	4 Table V	Fighter	55019	13	14 pp. B-88	F86-F	84591
		Tail	64833			Horizontal	131586
			68430		B-89	Stabilizer	150384

TABLE 2 [Continued]

Group No.	Reference	Structure	Cycles
14	11 Table 3	Piston Provost Wing	177200 142192 124800 122192
15	12 Table 3	Piston Provost Wing	125248 130448 127984 80384 127760 120960 140800 140400 144400 100400 165600
16	15 Table 6	Vampire Wing (2L65)	430760 396940 590782 520472 459952 406552 354576 452476
17	15 Table 7	Vampire Wing (2L65)	383590 379318 406445 414028 370062 400856 380564 317196
18	16 Table VIII	Box Beam (7075-T6)	92777 56540 62190
19	16 Table VIII	Box Beam (7075-T6)	76140 83700 105840
20	16 Table VIII	Box Beam (7075-T6)	194040 212520
21	16 Table VIII	Box Beam (7075-T6)	261290 132182
22	16 Table VIII	Box Beam (7075-T6)	69660 36720 55080
23	16 Table VIII	Box Beam (7075-T6)	72756 52116 49794
24	13 Table 1 (i)	Piston Provost Wing	129200 155600 127600 148400 131200
25	8 Table VIII	Mustang Wing (24S-T)	1147000 912000 720000 924000 907000 751000
26	4 Table VI	Fighter Wing	45963 51299 44765
27	15 Table VIII	Vampire Wing (2L65)	466716 366324
28	13 Table 1 (ii)	Piston Provost Wing	140400 104272 145120 114160 132000
29	13 Table 1 (iii)	Piston Provost Wing	145600 191200 215680 150000 267792
30	13 Table 1 (iv), (v) (vi)	Piston Provost Wing	130640 160000 132640 114432 155760 102880 87360 117600 179264 149440 201344

TABLE 3

Fatigue Life Data—Loading Including Ground to Air Cycles

Group No.	Reference		Structure	Cycles
1	5	Table 2	Britania Wing Joint	981205 987440 1294976 1082724 1083724
2	7	Table 103 (Fig. 26)	Builtup panel	638764 765582
3	9	Table 2	Friendship Wing	124121 115706
4	9	Table 2	Friendship Wing	100707 79726
5	8	Table VIII	Mustang Wing	485000 1053000 668000 272000 542000 979000 961000 1101000 775000 855000
6	4	Table VI	Fighter Wing	37575 58338
7	7	Table 104 (Fig. 27)	Builtup panel	218881 394309

TABLE 4

Gust Loading Data—Analysis

Group No.	Numbers of load Levels Up/Down	Loading Sequence	No. of Specs.	Lognormal $\bar{x}$ Log Cycles	Lognormal s	Weibull β Cycles	Weibull α
1	3/3	Program	4	6·175	0·158	1761000	3·238
2	3/3	,,	7	6·085	0·165	1455000	3·027
3	16/16	,,	6	6·985	0·091	10635000	5·641
4	16/16	,,	4	5·804	0·069	681000	8·954
5	36/36	,,	2	5·974	0·042	974000	17·668
6	19/19	,,	3	5·938	0·042	898000	18·343
7	15/15	,,	2	5·342	0·073	233000	10·128
8	11/11	Random	10	6·436	0·182	3323000	2·754
9	15/15	,,	2	5·243	0·108	191000	6·828

TABLE 5

Manoeuvre Loading Data—Analysis

Group No.	No. of Load Levels: Up/Down	No. of Load Levels: Lower Bound	Loading Sequence	No. of Specs.	Lognormal: $\bar{x}$ Log Cycles	Lognormal: s	Weibull: β Cycles	Weibull: α
1	5/1	Constant	Program	4	4·813	0·088	71300	5·582
2	5/1	,,	,,	4	4·798	0·088	68000	7·684
3	11/1	,,	,,	3	5·843	0·152	800000	4·306
4	4/1	,,	,,	3	4·636	0·071	46400	7·561
5	10/1	,,	,,	2	4·902	0·019	81000	37·975
6	4/1	,,	,,	3	4·491	0·121	34400	6·013
7	5/1	,,	,,	3	4·951	0·114	99000	5·808
8	5/1	,,	,,	3	4·981	0·094	104000	8·447
9	4/1	,,	,,	3	4·637	0·082	46600	8·471
10	5/1	,,	,,	3	4·558	0·052	37800	12·863
11	5/1	,,	,,	3	4·796	0·049	65200	14·636
12	6/6	Gust	,,	41	5·180	0·087	167000	5·237
13	5/1	Constant	,,	3	5·075	0·131	133000	5·582
14	6/6	Gust	,,	4	5·146	0·074	151000	6·580
15	6/6	,,	,,	11	5·099	0·084	136000	7·042
16	6/6	,,	,,	8	5·650	0·070	483000	6·537
17	6/6	,,	,,	8	5·580	0·036	393000	19·073
18	4/1	Constant	,,	3	4·838	0·114	77000	4·724
19	5/1	,,	,,	3	4·943	0·074	94200	7·487
20	6/1	,,	,,	2	5·308	0·028	208000	26·375
21	6/1	,,	,,	2	5·269	0·209	220000	3·521
22	6/1	,,	,,	3	4·716	0·141	59100	4·705
23	5/1	,,	,,	3	4·759	0·090	62700	5·936
24	6/6	Gust	,,	5	5·140	0·039	144000	12·826
25	12/9	Gust	Random	6	5·946	0·073	955000	6·651
26	4/1	Constant	,,	3	4·674	0·031	48700	17·185
27	6/6	Gust	,,	2	5·616	0·074	439000	9·906
28	6/6	,,	,,	5	5·101	0·061	134000	10·185
29	6/6	,,	,,	5	5·276	0·111	212000	4·632
30	6/6	,,	,,	11	5·132	0·107	152000	4·688

TABLE 6

Data Including Ground to Air Cycles—Analysis

Group No.	Type of Loading	Loading History: No. Load Levels Up/Down	Loading History: Lower Bound	Loading History: Loading Sequence	Loading History: Cycles per GA Cycle	No. of Specs	Lognormal: $\bar{x}$ Log Cycles	Lognormal: s	Weibull: β Cycles	Weibull: α
1	Gust	7/7	Gust	Program	64	5	6·034	0·049	1140000	9·228
2	,,	19/19	,,	,,	Complex	2	5·845	0·056	731000	13·249
3	,,	15/15	,,	,,	12·5	2	5·079	0·022	122000	34·177
4	,,	15/15	,,	Random	12	2	4·952	0·072	94900	10·270
5	,,	11/11	,,	,,	≈36	10	5·854	0·190	857000	3·495
6	Manoeuvre	4/1	Constant	Program	13	2	4·670	0·135	52200	5·454
7	,,	11/1	,,	Random	Complex	2	5·468	0·181	340000	4·076

TABLE 7

Structural Fatigue Life Variability—Lognormal Analysis

(a) Gust Loading

Loading Spectrum: Upper	Lower	Loading Sequence: Program		Random	Pooled
Gust	Gust	0·120 (28, 21)	↔ N.S.	0·176 (12, 10)	0·141 (40, 31)

(b) Manoeuvre Loading

Loading Spectrum: Upper	Lower	Loading Sequence: Program		Random	Pooled
Manoeuvre	Gust	0·079 (77, 71)	↔ N.S.	0·094 (29, 24)	0·083 (106, 95)
		↕ N.S.		↕ N.S.	↕ N.S.
Manoeuvre	Constant	0·103 (53, 35)	↔ N.S.	0·031 (3, 2)	0·100 (56, 37)
Pooled		0·087 (130, 106)	↔ N.S.	0·090 (32, 26)	0·088 (162, 132)

(c) Loading including Ground Air Cycles

Loading Spectrum: Upper	Lower	Ground Air Cycle	Loading Sequence: Program		Random	Pooled
Gust	Gust	Simple	0·045 (7, 5)	→	0·182 (12, 10)	0·147 (21, 16)
			↕ N.S.	← Sig		
Gust	Gust	Complex	0·056 (2, 1)			
Manoeuvre	Constant	Simple	0·135 (2, 1)	←		0·160 (4, 2)
				N.S.		
Manoeuvre	Constant	Complex		→	0·181 (2, 1)	

Entries show standard deviation of log life, with number of test specimens and degrees of freedom, respectively, in parentheses.

N.S.: F test comparison of variances not significant at 5% level.

Sig.: F test comparison of variances significant at 5% level.

TABLE 8

Structural Fatigue Life Variability—Weibull Analysis

(a) Gust Loading

Loading Spectrum		Loading Sequence		Pooled
Upper	Lower	Program	Random	
Gust	Gust	4·708 (28)	2·987 (12)	3·934 (40)

(b) Manoeuvre Loading

Loading Spectrum		Loading Sequence		Pooled
Upper	Lower	Program	Random	
Manoeuvre	Gust	6·092 (77)	5·620 (29)	5·966 (106)
Manoeuvre	Constant	6·529 (53)	17·185 (3)	6·740 (56)
Pooled		6·233 (130)	5·918 (32)	6·171 (162)

(c) Loading Including Ground Air Cycles

Loading Spectrum			Loading Sequence		Pooled
Upper	Lower	Ground Air Cycle	Program	Random	
Gust	Gust	Simple	10·844 (7)	3·893 (12)	5·441 (21)
Gust	Gust	Complex	13·25 (2)	—	
Manoeuvre	Constant	Simple	5·454 (2)	—	4·665 (4)
Manoeuvre	Constant	Complex	—	4·076 (2)	

Entries show dispersion parameter of fatigue life, with number of test specimens in parentheses.

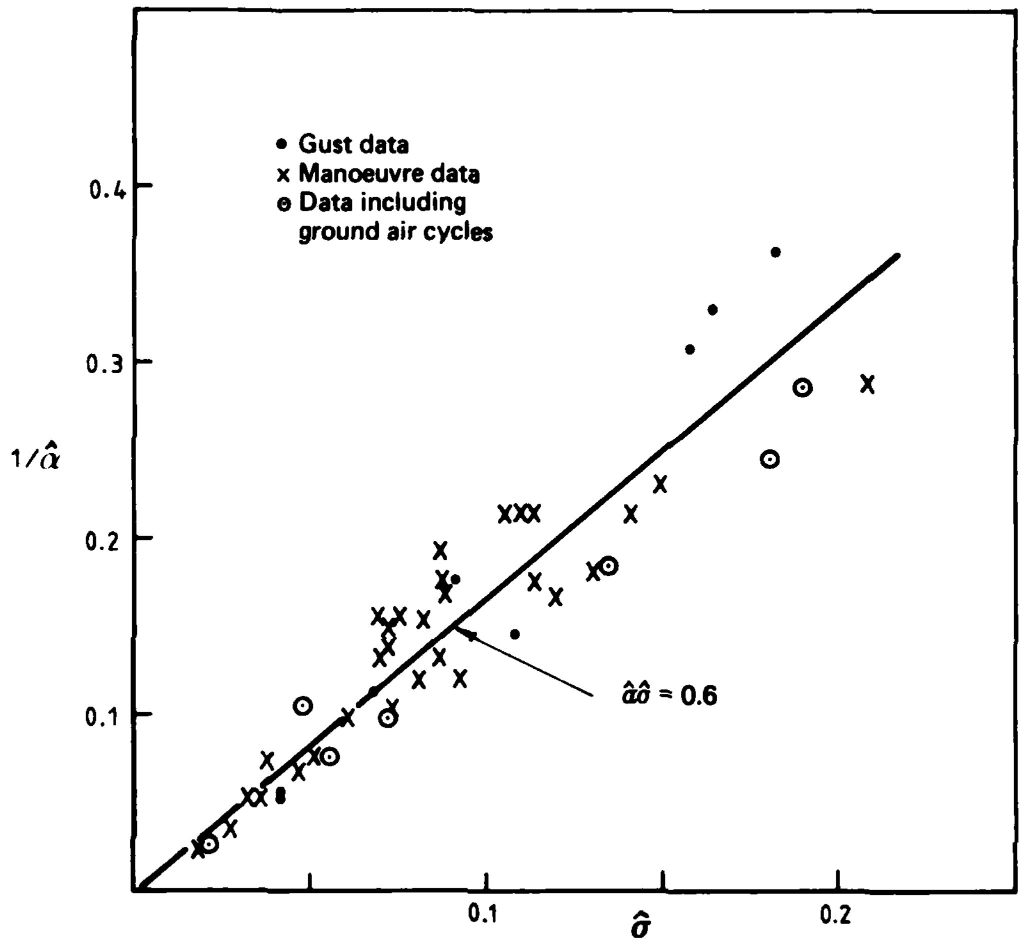

FIG. 1 RELATION BETWEEN LOGNORMAL STANDARD DEVIATION, $\hat{\sigma}$, AND RECIPROCAL OF WEIBULL DISPERSON PARAMETER, $\hat{\alpha}$

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